

COMBINED HYPERSPATIAL AND HYPERSPECTRAL IMAGING SPECTROMETER CONCEPT

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1. INTRODUCTION

There is a user need for increasing spatial and spectral resolution in Earth Observation (EO) optical instrumentation. Higher spectral resolution will be achieved by the introduction of spaceborne imaging spectrometers. Higher spatial resolutions of 1 - 3 m will be achieved also, but at the expense of sensor redesign, higher communications bandwidth, high data processing volumes, and therefore, at the risk of time delays due to large volume data-handling bottlenecks.

This paper discusses a design concept whereby the hyperspectral properties of a spaceborne imaging spectrometer can be used to increase the image spatial resolution, without such adverse cost impact.

2. HYPERSPATIAL IMAGE MERGING

An EO instrument may be designed so as to provide higher spatial resolution information through combining more than one "look" of a scene at different wavelengths. These multiple "looks" have subpixel offsets from each other. The composite image has a higher sampling density, and hence a higher spatial resolution if the system SNR is adequate. With the images combined from different wavelengths, the composite image represents what would have been measured by a high-resolution "pseudo-panchromatic band". Sharpe and Kerr (1991) had success in producing hyperspatial images from multispectral Landsat-5 TM data to verify this concept.

Figure 1 shows a process by which spatially offset multispectral images ("looks") can be combined to increase spatial resolution. Combining the single-band images from a multispectral sensor increases the number of samples, but the samples are taken from different parts of the spectrum. Consequently, the first step is *radiometric matching*, in which the radiance levels in each of the single-band images are modified, over localized regions, to simulate those in a reference band. The second step consists of merging the radiometrically matched images to form a composite image; this is called *band interleaving*. The third step is *geometric rectification*, where the composite image is resampled onto a uniform grid.

When the single-band images are combined, the distance between the pixels decreases, but the pixel size (amount of ground covered by each individual pixel) remains the same; consequently, the pixels are overlapped. *Pixel shrinking filters* (Wornell *et al.*, 1989) are then used to produce pixels that no longer overlap but are butted. This simulates an image that would have been measured with detectors having a pixel size equal to the new pixel spacing. The net result is a new composite image that has higher spatial detail, and may be said to have an effectively higher Modulation Transfer Function (MTF) than each original single-band image.

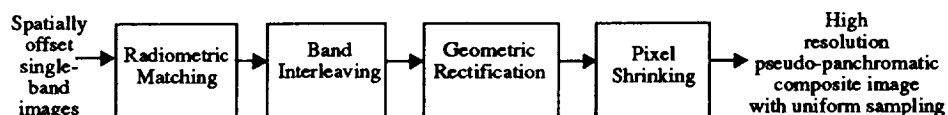


Figure 1 Hyperspatial Image Merging Process

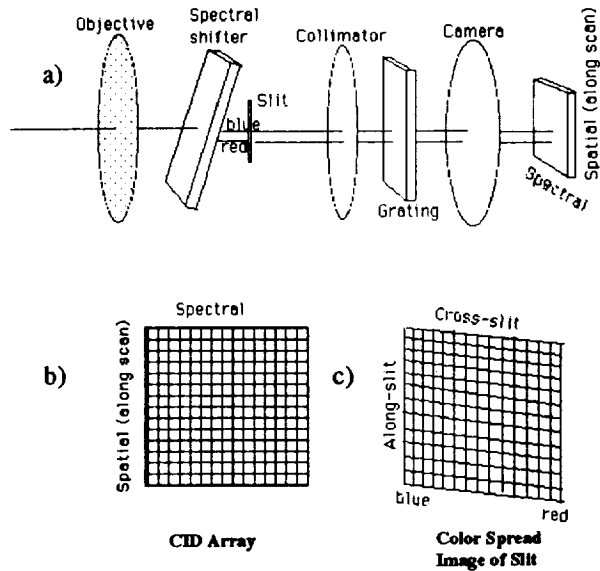


Figure 2 Hyperspatial Imaging Spectrometer Design

3. HYPERSPATIAL IMAGING SPECTROMETER CONCEPT

This section shows that a hyperspatial-hyperspectral instrument can be readily designed. Figure 2a shows the optics layout for a typical Imaging Spectrometer (IS) (ignoring the “spectral shifter” and the fact that the array consists of Charge Injection Devices (CIDs) for the moment). The grating serves to disperse the light in the “spectral” dimension, projecting the various colors on different pixels as shown in Figure 2b. In order to allow the image merging process outlined in Figure 1 to be applied to this IS, spatial shifts between the different bands in the along-scan direction plus appropriate band-to-band time delayed readouts among the spectral bands for the across-scan direction are required.

The random access CID array is a detector readout addressable matrix, so that individual detectors and therefore bands can be read out under external control. This means that with a random access CID the spectral bands can be read out in whatever band sequence is desired and with selectable time delays between individual bands. The random access CID then can provide the necessary across-scan direction subpixel spatial shifts between the single-band images.

It is desirable to also introduce a differing subpixel shift between each single-band image in the along-scan direction (orthogonal to the grating dispersion). As the shift between band centres in the along-scan direction is not programmable by readout (only by unit detector sizes), it is necessary to introduce a spectral shifter to produce the required subpixel offsets. This device is shown near the slit in Figure 2a. This optical device creates a different relative subpixel image shift for each band (color) along the length of the slit. The color spread image of the slit is shown in Figure 2c, with the degree of along-slit displacement from the optical axis being proportional to the wavelength of observation.

The resulting single-band images are displaced from each other by subpixel amounts in both the along-scan and across-scan directions. The subpixel shifts can be made to be uniform in the across-scan direction by appropriate choices of the detector readout times. The subpixel shifts in the along-scan direction, on the other hand, are determined by the spectral dispersion of the spectral shifter for each band wavelength. This will be somewhat nonuniform, but the nonuniformity can be handled by subsequent processing.

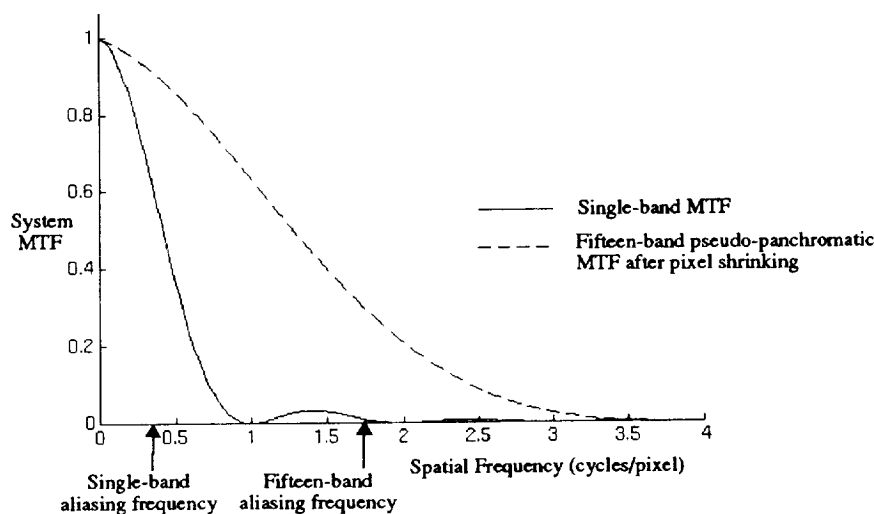


Figure 3 Simulated single-band and pseudo-panchromatic MTFs in the across-scan direction (at 680 nm) for a 15-spectral band IS instrument

4. HYPERSPATIAL RESOLUTION OF AN IMAGING SPECTROMETER

The quality of an imaging system can be described by two parameters: the system MTF* and the aliasing frequency. The spatial frequency at which the first reflected branch of the MTF (caused by sampling the image) is one-half of the fundamental branch (true spectrum centered about zero) is called the *aliasing frequency*** . A convenient definition is to set the *spatial resolution**** to be the inverse of the aliasing frequency.

In order to illustrate the benefits of the IS design shown in Figure 2, a 15-spectral band silicon CID IS will be used as an example. Figure 3 shows the simulated system MTF in the across-scan direction at 680 nm as a solid curve. If the sensor had its optics set up as shown in Figure 2, there would be different subpixel displacements between all fifteen spectral bands. Suppose the spectral shift and readout timing were coordinated so that all fifteen single-band images were evenly offset from each other by subpixel amounts in both the along-scan and across-scan directions**** . Processing these images through the flowchart in Figure 1 up to the pixel shrinking algorithm would leave the MTF shape unchanged and the aliasing frequency increased by a factor of about $\sqrt{15}$ (as shown in the figure), since the sampling density has increased by this amount in both spatial directions.

A pixel shrinking filter is then used to change the single-band MTF to the fifteen-band pseudo-panchromatic MTF (shown as a dotted curve in Figure 3). The result of these operations is a better MTF with a higher aliasing frequency, yielding a significant increase in spatial resolution and image quality. The increase in spatial resolution is limited by the shape of MTF, and the SNR achieved. Combining N multispectral images evenly offset in both spatial directions will yield an increase in resolution of about \sqrt{N} .

* The MTF is different in the along-scan and across-scan directions. The across-scan MTF is a function of the detector size, optics, and sampling rate.

** This definition has the added provision that the reflected branch be, on average, greater than the fundamental branch for spatial frequencies above the aliasing frequency.

*** This definition of spatial resolution is very conservative; discernible detail will be noticeable below this limit.

**** The bands are not expected to be evenly spaced in the spectrum so the subpixel displacement in the along-scan direction will not be uniform.

5. USING AVIRIS DATA TO INVESTIGATE THE COSTS AND BENEFITS OF A HYPERSPATIAL IMAGING SPECTROMETER DESIGN

A hyperspatial-hyperspectral IS instrument has been conceptually modeled. The next stage in the analysis consists of testing the design concept proposed here with real data. Spaceborne IS data will be simulated from airborne IS data for these tests. Each band of the airborne data will be "smoothed" to the resolution of the proposed spaceborne sensor. During this process, the simulated bands will be offset by subpixel amounts. The pseudo-panchromatic composite image will be created from these simulated bands and directly compared with the original "unsmoothed" high resolution single-band images. The large spectral range and contiguous nature of the AVIRIS spectral bands make it well-suited to these tests, since they allow significant flexibility in the simulation of spaceborne imagery.

The main parameters to investigate are the spatial resolution of the pseudo-panchromatic composite image, the surface characteristic conditions under which hyperspatial image merging can be utilized, and the use of the high resolution pseudo-panchromatic image in typical applications. The spatial resolution of the pseudo-panchromatic composite image can be tested by comparing it to the individual smoothed single-band images to search for improved spatial detail, and by comparing it to the original unsmoothed high resolution images. The later tests will consist of comparing edge sharpness at feature edges, calculating rms differences, and visually comparing the simulated and original high resolution images.

Tests to determine the conditions under which hyperspatial image merging should be utilized, and its robustness in the presence of errors in data gathering and processing, should also be conducted. This will yield information about how the improvement in spatial detail varies with the number of bands merged, the effect of the accuracy of pixel location knowledge, and tolerance of the hyperspatial image merging process to different band wavelengths.

The limitations of implementing this new design also need to be addressed. This consists of investigating how the radiometric accuracy and SNR among single-band images are affected by subpixel displacements, and investigating whether image misregistration causes appreciable error in the derivation of standard thematic products, such as the Normalized Difference Vegetation Index (NDVI).

6. CONCLUSIONS AND RECOMMENDATIONS

The design concept presented in this paper uses the hyperspectral properties of an imaging spectrometer to achieve hyperspatial resolution. The benefits include better image spatial quality via a better MTF. The next stage consists of using airborne multispectral imagery to test the design concept for high spatial resolution spaceborne imaging spectrometers, and to test the limitations of the design. AVIRIS seems well-suited to these studies due to its wide spectral range and the contiguous nature of its spectral bands.

7. BIBLIOGRAPHY

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